8 NUCLEAR CHEMISTRY

Nuclear chemistry *is the study of nuclear reactions and their uses in chemistry.* The phenomenon of radioactivity was discovered by Henri Becquerel in 1896. He accidentally discovered that uranium minerals emit a radiation similar to X – rays. *Elements such as uranium, thorium and radium that spontaneously emit radiation without absorbing energy are called* **radioactive elements** *and the property or phenomenon of giving out these radiations is called* **radioactivity.** The term radioactivity was first used by *Marie Curie.*

When nuclei change spontaneously, emitting radiation, they are said to be **radioactive.** Radioactivity is essentially a nuclear phenomenon and is a drastic process because the element changes in kind. It is spontaneous and an irreversible self-disintegrating activity.

8.1 Natural Radioactivity

Naturally occurring elements like uranium, polonium, radium etc. are constantly undergoing a spontaneous change and as a result of this they are emitting α–,β– and γ– rays and thus change into other elements. This spontaneous change is called **natural radioactivity.** In natural radioactivity only a single nucleus is involved and it is always found in heavier elements.

The nucleus contains protons and neutrons, both of which are called **nucleons.** Nuclei that are radioactive spontaneously emit radiation. These radioactive nuclei are called **radionuclides** and the atoms containing them are called **radioisotopes.**

Nuclear Equations

Radionuclides are unstable and spontaneously emit particles and electromagnetic radiation. Emission of radiation is one of the ways in which an unstable nucleus is transformed into a more stable one with less energy. The emitted radiation is the carrier of the excess energy. For example, uranium –238 nucleus represented by the nuclide symbol $^{238}_{92}U$ spontaneously emit helium –4 nuclei. The helium –4 particles ($^{4}_{2}He$) are known as **alpha particles,** and a stream of these particles is called **alpha radiation.** The decay of $^{238}_{92}U$ by alpha-particle emission is written as

$$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

The product, in addition to He –4, is thorium. This is an example of **nuclear equation,** which *is a symbolic representation of a nuclear reaction. "The process in which a nucleus spontaneously disintegrates, giving of radiation, is called* **radioactive decay.**" The nuclide undergoing a decay is called **parent nuclide,** and the nuclide produced (along with a small particle) is called the **daughter nuclide.** The ^{238}U is the parent nuclide and the ^{234}Th is the daughter nuclide.

A daughter nuclide may itself be unstable. Thorium –234 undergoes beta decay.

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + \underset{\beta\text{ – particle}}{{}^{0}_{-1}e}$$

The daughter protactinium has one more proton than the parent $^{234}_{90}Th$ nuclide.

When a beta particle was emitted from the nucleus, a neutron was evidently converted into a proton.

$$^{1}_{0}n \longrightarrow {}^{1}_{1}P + {}^{0}_{-1}e$$

Gamma emission is often not explicitly shown in nuclear equations, since neither mass nor charge change during this kind of emission. A **gamma photon** *is a particle of electromagnetic radiation of short wavelength (about 1pm or 10^{-12} m) and high energy.*

Types of Radioactive Rays

When a radioactive material (uranium mineral) is placed between electric plates or poles of a strong magnet, the radiation separates out into three different kinds, called *alpha, beta* and *gamma* rays. The alpha (α) rays deflected to the negative plate, must be composed of positively charged particles. The beta (β) rays, more sharply deflected to the positive plate, must be composed of lighter, negatively charged particles . The gamma (γ) rays, undeflected, must be electrically neutral.

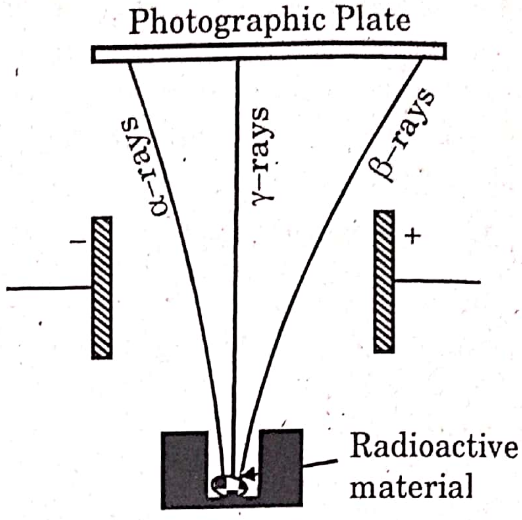

Fig. 8.1 Separation of Radioactive Rays

α-particles. The α-particles caries two unit positive charges and has a mass of a helium nucleus, designated as $^{4}_{2}He$. The velocity of α-rays depends upon the radioactive substance from which they are emitted. They produce intense ionization in the gas through which they pass. They have the shortest penetrating power. In fact, *their penetrating power is inversely proportional to their ionizing power.* They affect a photographic plate and produce fluorescence (i.e., lumiscence) when strike a fluorescent screen like ZnS.

β-particles. The electric charge and mass of a beta (β) particle show it to be an electron, represented by $^{0}_{-1}e$ and have a velocity about ten times greater than that of α-rays. Their e/m ratio resembles that of electrons. Due to smaller mass they can penetrate a few mm into metals. They affect photographic plates more strongly than α-particles. Moreover, their power of ionizing gaseous molecules is much less than that of α-particles.

Gamma (γ) rays: γ-rays do not consist of charged particles but they are highly energetic radiation. They are therefore similar to X-rays, except that their wavelength are shorter. Gamma rays are photons several million times higher in frequency than visible light. Thus γ-rays are *non-material* in nature. They travel with the velocity of light. They are more penetrating than the α- and β-rays and at the same time are weak ionizer of gases.

Group displacement Law: The emission of α- and β-particles from the radioactive nuclei results in displacement of position of product of disintegration in periodic table as the atomic number of the parent element is changed. The results of α- and β-emissions are summed up in the form of **Group displacement law.** It states that *"An element by the emissions of an α-particle moves two places to the left (i.e., atomic number decreases by 2) and mass of the element is decreased by 4 units, and an element by the emission of a β-particle moves one place to the right (i.e., Atomic number increases by 1) in the periodic table."* This generalization was first achieved by Fajans and Soddy (1913) and is known as 'Fajans-Soddy Group displacement law'. This law is self evident, since an α-emission decreases the atomic number of the parent element by the 2 and β-emission increases the atomic number by 1.

1. Alpha emission: Emission of a $^{4}_{2}He$ or alpha particle, from an unstable nucleus.

$$^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$

The product nucleus has an atomic number that is two less, and a mass number that is four less, than that of the original nucleus.

2. Beta emission: Emission of a high speed electron from an unstable nucleus. Beta emission is equivalent to the conversion of a neutron to a proton.

$$^{1}_{0}n \longrightarrow {}^{1}_{1}P + {}^{0}_{-1}e$$

Thorium undergoes beta decay.

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

The product nucleus has an atomic number that is one more than that of the original nucleus. The mass number remains the same.

3. Gamma emission: Emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about 10^{12} m.

Table 8.1 Common particles in Radioactive decay and Nuclear Transformations.

Particle	Symbol
Alpha particle	$^{4}_{2}He$ or $^{4}_{2}\alpha$
Beta particle	$^{0}_{-1}e$ or $^{0}_{-1}\beta$
Gamma particle	γ
Neutron	$^{1}_{0}n$
Proton	$^{1}_{1}H$ or $^{1}_{1}P$
Electron	$^{0}_{-1}e$
Positron	$^{0}_{+1}e$

4. Positron emission: Emission of a positron from an unstable nucleus. A **positron** *is a particle that has the same mass as an electron but a positive charge.* The positron is represented as $^{0}_{1}e$. Carbon −11 is an example of an isotope that decays by positron emission.

$$^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{1}e$$

The emission of a positron has the effect of a converting a proton to a neutron, thereby decreasing the atomic number of nucleus by 1:

$$^{1}_{1}P \longrightarrow {}^{1}_{0}n + {}^{0}_{1}e$$

5. Electron Capture: *The decay of an unstable nucleus by capturing, or picking up, an electron from an inner orbital of an atom.* Rubidium −81 undergoes decay in this fashion.

$$^{81}_{37}Rb + ^{0}_{-1}e \text{ (orbital electron)} \longrightarrow ^{81}_{36}Kr$$

Electron capture, like positron emission, has the effect of converting a proton to a neutron.

$$^{1}_{1}P + ^{0}_{-1}e \longrightarrow ^{1}_{0}n$$

Positron are annihilated as soon as they encounter electrons. When positron and an electron collide, both particles (Positron and electron) vanish with the emission of two gamma photons that carry away the energy.

$$^{0}_{1}e + ^{0}_{-1}e \longrightarrow 2\,^{0}_{0}\gamma$$

Example 8.1: Write the nuclear equation for the radioactive decay of radium –226 by alpha decay to give radon –222. The atomic number of radon is 88.

Solution: A radium –226 nucleus emits one alpha particle leaving behind a radon –222 nucleus. The nuclear equation is

$$^{226}_{88}Ra \longrightarrow ^{222}_{86}Rn + ^{4}_{2}He$$

8.3 Artificial or Induced Radioactivity

Artificial radioactivity *is a process by which an element is converted into a new radioactive isotope of a known element by artificial means.*

Artificial radioactivity is induced by bombardment of certain nuclei with subatomic particles (or atoms), which are produced either by other nuclear reactions or in machines referred to as **atom smashers.** The first artificially induced nuclear reaction was performed by Ernest Rutherford in 1919. He bomarded nitrogen –14 with alpha particles from the radioactive decay of radium. The product nuclides were oxygen –17 plus a proton. The reaction is

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

In 1934, Irene Jaliot-Curie, the daughter of Marie Curie, while treating light elements such as boron or Al with α-particles, detected the emission of positrons and neutrons. They observed that the emission of positrons does not stop when the source of α-particles is removed. The reactions are

$$^{10}_{5}B + ^{4}_{2}He \longrightarrow ^{13}_{7}N + ^{1}_{0}n$$

followed by

$$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{+1}e$$

$^{13}_{7}N$ was the first radioisotope to be produced artificially. Several small particles, in addition to those involved in natural radioactivity, are involved in artificial nuclear reactions. These reactions are examples of artificial **transmutation** – the change of one element into another. Such reactions have permitted the synthesis of hundreds of radioisotopes in the laboratory.

8.4 Stability of Nuclei and Neutron-Proton ratio

Nuclei are composed of protons and neutrons. The protons would tend to fly apart due to repulsive forces between them, but the neutrons in some way hold the protons together within the nucleus. The **stability of a nucleus** *seems to depend on the ratio of the number of neutrons (N) and protons (P) present in the nucleus.* All nuclei with two or more protons contain neutrons.

1. Stable nuclei with low atomic numbers (up to about 20) have approximately equal numbers of neutrons and protons i.e., N/P = 1
2. For nuclei with higher atomic number, the nuclei to be stable, there must be more number of neutrons than the number of protons i.e., N/P > 1.
3. When there are more than 83 protons in a nucleus, no number of neutrons will stabilize it.

By plotting a graph between number of neutrons (N) and of protons (P) for the nuclei of various elements it has been found that most of the *stable nuclei (non-radioactive nuclei)* lie in a well-defined belt which is known as the **zone** or **belt of stability** because it contains the stable nuclei. (See Fig. 8.2). *The belt of stability ends at element 83 (bismuth). All nuclei with 84 or more protons (atomic number ≥ 84) are radioactive.* Nuclides outside the belt of stability are generally radioactive. We can envision three general situations.

1. Nuclides to the left of the belt of stability have a N/P ratio large than needed for stability. These nuclides tend to decay by beta emission. Beta emission reduces the N/P ratio, because in this process a neutron is changed to a proton.

2. Nuclides to the right of the belt of stability have a N/P ratio smaller than needed for stability. These nuclides tend to decay by either positron emission or electron capture. Both processes convert a proton to a neutron, increasing the N/P ratio and giving a stabler product nuclide.

3. Nuclides of atomic numbers greater than 83, often decay by alpha emission.

Two further observations are useful in predicting nuclear stability.

1 Nuclei with 2, 8, 20, 28, 50 or 82 protons or 2, 8, 20, 28, 50, 82 or 126 neutrons are generally more stable than nuclei that do not contain these numbers of nucleons. These numbers of protons and neutrons are called **magic numbers**.

2 Nuclei with even numbers of both protons and neutrons are generally more stable than those with odd numbers of nucleons.

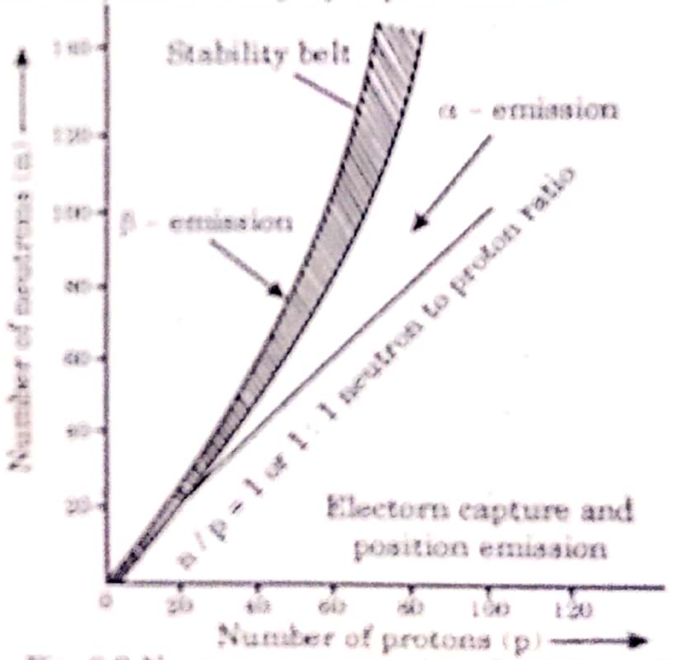

Fig 8.2 Neutron-proton ratios of stable nuclei

The protons and neutrons in a nucleus appear to have energy levels much as the electrons in an atom have energy levels. *The* ***shell model of the nucleus*** *is a nuclear model in which protons and neutrons exist in levels, or shells, analogous to the shell structure that exists for electrons in an atom.* In an atom, filled shells of electron are associated with the special stability of **noble gases**. Experimentally it is noted that nuclei with certain number of protons or neutrons appear to be very stable. These numbers, called magic number and associated with